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MODGRO

User's Manual

Version 1.2

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James A. Harter

February 1988

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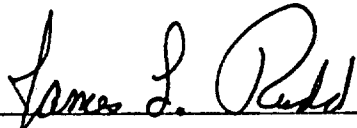


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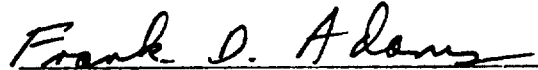
FOREWORD

This report was prepared by James A. Harter of the Structural Integrity Branch, Structures Division, Air Force Flight Dynamics Laboratory. The work was conducted in-house under work unit 24010179, "Life Analysis Methods."

This technical memorandum has been reviewed and is approved.



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February 88

Technical Memorandum, Apr 87 to Feb 88

MODGRO v1.2
User's Guide

24010179

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AFWAL-TM-88-157-FIBE

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MODGRO is a PC oriented crack growth analysis computer program. It is based on a program called ASDGRO written by E. Davidson, ASD/ENFSF, WPAFB, OH. The major differences between MODGRO and ASDGRO are:

- Acceptance of tabular da/dN data,
- Seperate 'user-friendly' input data generator, and
- Approximate K solutions for arbitrary geometries.

MODGRO is a tool that can analyze many common, as well as some uncommon, crack geometries. MODGRO inputs are normalized to allow the use of any system of units, however, it is up to the user to ensure consistency.

This software is distributed IAW AFR 300-6. Submit requests for software to:

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ABSTRACT

This report documents work done on a PC based crack growth analysis computer program (MODGRO). This program is based on a program called ASDGRO written by E. Davidson, ASD-ENFEEF, Wright Patterson AFB, OH. The major differences between MODGRO and ASDGRO are summarized as follows:

- o Acceptance of tabular da/dN data.
- o Separate "user friendly" input data generator, and
- o Approximate K solutions for arbitrary geometries.

MODGRO is a tool that can analyze many common, as well as some uncommon, crack geometries. Any system of units can be used. It is, however, up to the user to be sure that the units are consistent. A users manual is included as part of this report.

This software is distributed in accordance with AFR 300-6. Submit requests for the software to :

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INTRODUCTION

Over the years, many crack growth computer programs have been written (CRACKS, CRKGRO, ... , etc.) to analyze common structural geometries. Most successful programs have gone through many modifications, and have become very large and unwieldy. This is because it is impossible to anticipate every crack growth problem. When problems arise that cannot be accounted for, the programs are simply expanded as necessary. MODGRO is not intended to be the end-all in crack growth analysis; however, it takes the best features of many of its predecessors (along with some new ideas) and combines them in a single, manageable code. In this case, the code is in BASIC and runs on any IBM-PC or compatible computer.

As is true of many current crack growth routines, MODGRO is a descendant of the CRACKS series of programs. Its most recent predecessor is CRKGRO. MODGRO is essentially a more efficient version of CRKGRO in that it is more compact. It does not contain a plotting package, but will store crack length vs. life data for external plotting. In some areas MODGRO exceeds the capability of CRKGRO. These differences will be discussed in greater detail in the background section of this report.

MODGRO is written to predict crack growth under the assumptions of Linear Elastic Fracture Mechanics (LEFM). If the program is used in cases where plasticity is an issue, the user should be aware that the predictions are very likely to be in error.

BACKGROUND

While MODGRO is very similar to CRKGRO, there are a few differences. A table explaining how MODGRO performs crack growth analysis is given below. For those who are familiar with CRKGRO, a comparison between the two is also given in Table 1.

The major advantages of MODGRO include the ability to use a material data base library for crack growth rate and mechanical property data, an option to approximate stress intensity factor solutions for arbitrary stress fields, and the ability to import stress spectra of virtually any size. These capabilities were part of the modifications made to ASDGRO. The pre-processor for MODGRO (MODINP) was originally included in the source code for ASDGRO. However, MODGRO became too large for this and the pre-processor was taken out and made into a separate program. This allowed MODINP to be written so that input errors can be corrected interactively.

TABLE 1: Comparison Between MODGRO and CRKGRO

OPTION	MODGRO	CRKGRO
Pre-processor to edit and store input and spectrum data	YES	NO
Tabular da/dN - Delta K data	YES	NO
Walker Equation for da/dN - Delta K	YES (5 segments)	YES (2 segments)
Crack growth in 2 dimensions	YES	YES
Different da/dN - Delta K data for each direction	NO	YES
Generalized Willenborg Retardation Model	YES	YES
Chang Acceleration Model	NO	YES
Vroman Integration	YES	YES
Stress Intensity Factor solutions for common geometries (Newman - Raju)	YES	YES
Provides a means of analyzing arbitrary geometries	YES	YES
Analysis with load transfer	YES	NO
Load/Stress spectrum input: (Min-Max, R-Delta, Mean-Alt)	Min-Max	ALL
Checks for critical crack size at each stress level	YES	NO

The following sections explain the methods used in MODGRO.

Modelling da/dN - Delta K Data

There are two methods of determining the relationship between da/dN and delta K in MODGRO. The first is to use the Walker equation, and the second is to use tabular data. The Walker equation is given below.

$$da/dN = C (\Delta K (1-R))^{(m-1)p} \quad (1)$$

Since, by definition, $R = \text{minimum stress}/\text{maximum stress}$, the equation can be written as follows (for $R \geq 0$).

$$da/dN = C (K_{\max} (1-R)^{\frac{m}{p}}) \quad (2)$$

In the above equations, C , m , and p are material properties that must be input to MODGRO. Note that the constant p is used here instead of the usual n . This is because a conflict arises in the program between the constant N used for the number of cycles and the n in the standard Walker equation.

The Walker equation is a modification of the simpler Paris equation to account for stress ratio effects.

$$da/dN = C (\Delta K)^n \quad (3)$$

When plotted in log-log scale, for da/dN vs. K , the equations describe a straight line. In reality, da/dN - ΔK data is generally on a straight line over a limited range of da/dN values. A typical plot of da/dN vs. ΔK is shown in Figure 1.

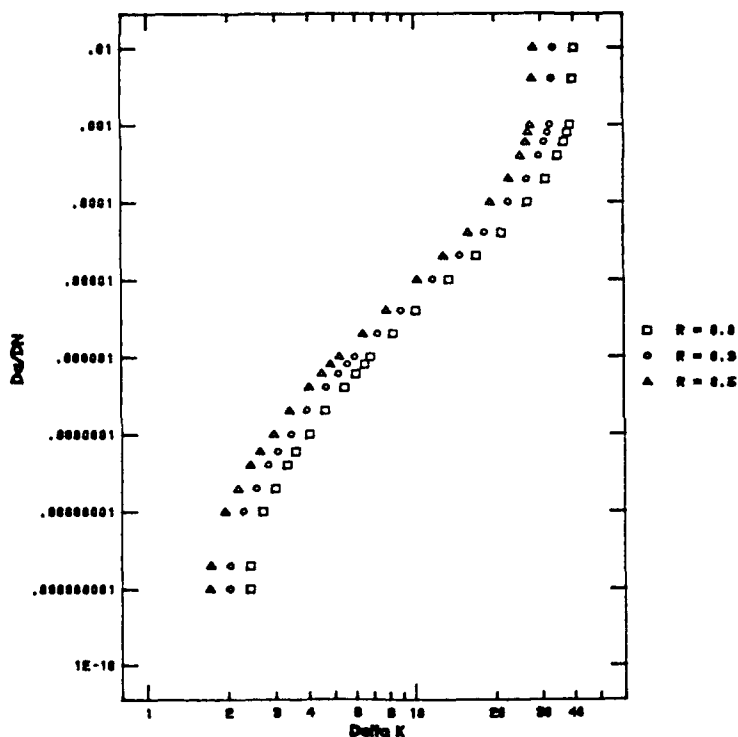


Figure 1 : Typical Plot of da/dN vs. ΔK Data

In order to approximate actual data, MODGRO allows the user to input values of C , m , and p for up to five curves. An example is presented in Figure 2 for three segments. As is shown in Figure 1, the data are also functions of the R value. The value of the variable, m , is used to account for the data shift as a function of R .

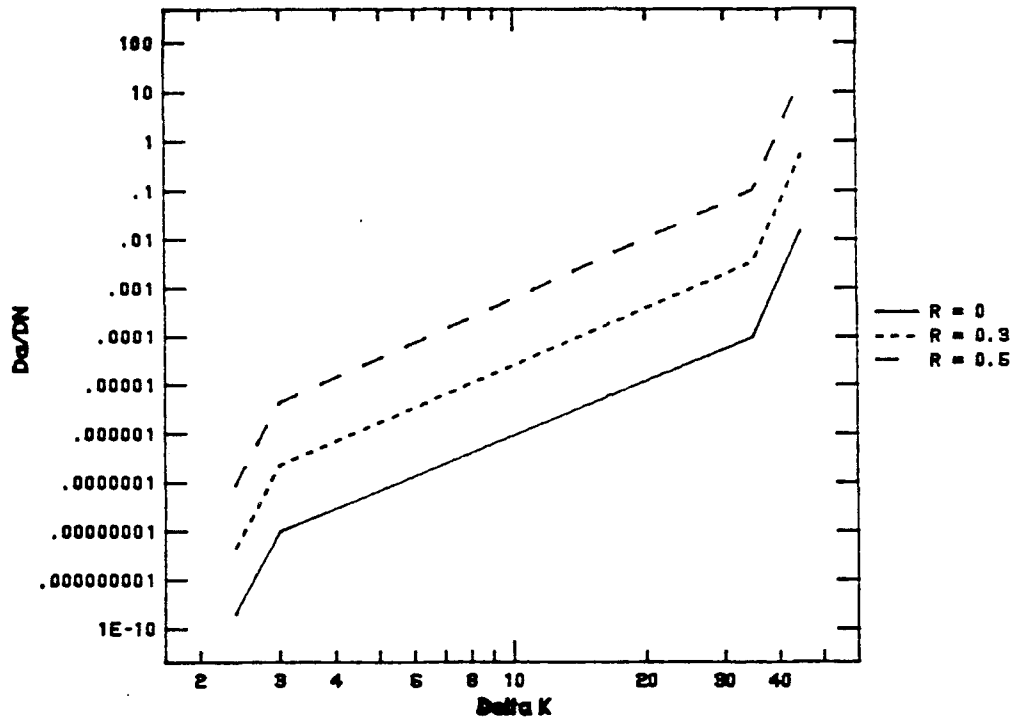


Figure 2 : Using the Walker Equation with 3 Segments

In the case where $R < 0$, ΔK is set equal to K_{max} . This is because the stress intensity factor is not defined for a stress that does not open the crack. MODGRO only considers the crack opening mode (Mode I). If the data were plotted for $R < 0$, the points would also appear to the left of the curve for $R = 0$. When the data are represented in this way, there is a value of R below which there is no further shifting. This makes physical sense since, in general, a crack can only be shut so far (assuming LEFM assumptions apply). The exact value of R varies with material, but is usually between $-.3$ and $-.6$.

It should be noted that when the standard Walker equation is used, the R shift is parallel for each line (in log-log scale). This can be a source of significant error when predicting crack growth due to spectrum loading.

The second method of characterizing crack growth data is by using tabular data. MODGRO uses 25 pairs of tabular da/dN - ΔK data. It is analogous to using 24 Walker lines. In order to minimize the input data required and still retain a high degree of accuracy, the author developed the following technique.

At a given crack growth rate, there are different values of delta K for each R. By applying the Walker equation (equation 1) for a single crack growth rate, the following relationship may be seen (Note: at a constant crack growth rate, C and p are constants).

$$\Delta K_1^{(m-1)} (1-R_1) = \Delta K_2^{(m-1)} (1-R_2) = \Delta K_3^{(m-1)} (1-R_3) = \dots \quad (4)$$

This is shown below in Figure 3.

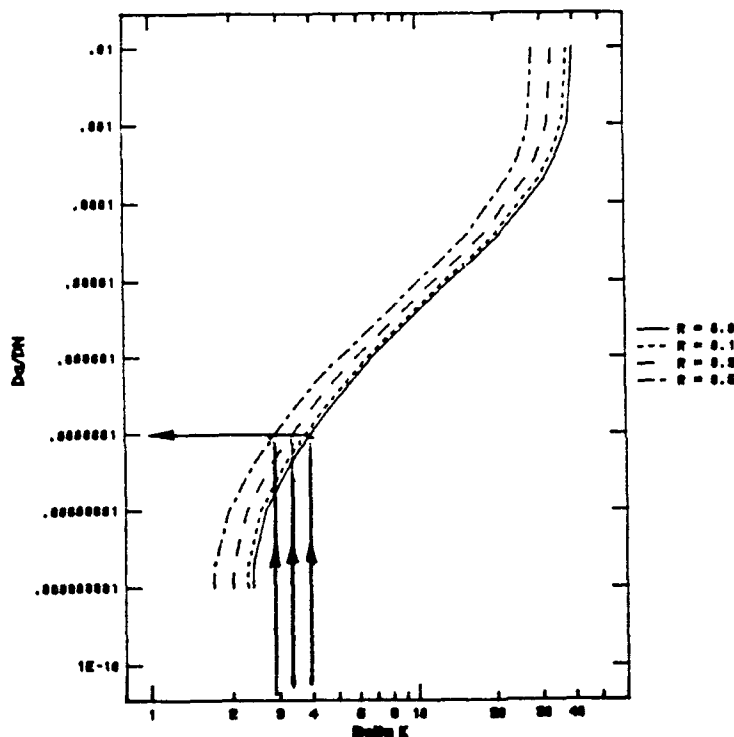


Figure 3 : Using Tabular Data with a Walker Shift at a Given Rate

Since R and delta K are known quantities in a crack growth rate test, only one equation is required to determine the value of m for a given crack growth rate. Therefore, data for two R values are all that are necessary to find m values for each of the 25 data points. However, additional data are very useful in checking the accuracy of this approach. In general, it is better if the R values for the data used to calculate m are not close together. For example, it is better to use data for R = 0.0 and R = 0.5 than R = 0.0 and R = 0.1. It should be noted that when fitting m values, negative m values should not be used. In case negative m values are required, use very small positive numbers instead and accept the error in the fit. The use of negative values can prevent a generated $da/dN - \Delta K$ curve from having a unique crack growth rate at a given ΔK .

Tabular data used in MODGRO are as follows: da/dN , ΔK for $R = 0.0$, and m (25 of each). ΔK for $R = 0$ is used because the equality given in equation 5 reduces to a simpler form. Also, since ΔK for $R < 0$ is considered to be K_{max} , the data at $R = 0.0$ are convenient references for the data on either side. The relationship between ΔK at $R = 0$ and ΔK at another R value is shown below.

$$\Delta K = \Delta K (@R=0) * (1-R)^{(1-m)}, \text{ for } R \geq 0 \quad (5)$$

$$\Delta K = \Delta K (@R=0) * (1-R)^{-m}, \text{ for } R < 0 \quad (6)$$

Note: ΔK is assumed to be equal to K_{max} when $R < 0$

The program places no restriction on the units. It is up to the user to insure that all units are compatible. This will be discussed in more detail later.

Retardation Model

MODGRO uses the Generalized Willenborg retardation model to account for the effect of load sequence. The model uses an 'effective' stress intensity factor based on the size of the yield zone in front of the crack tip. The formulation of the Willenborg retardation model that is used in MODGRO is given below.

$$K_{max}(eff) = K_{max} - K_r \quad (7)$$

$$K_{min}(eff) = K_{min} - K_r \quad (8)$$

$$R(eff) = K_{min}(eff)/K_{max}(eff) \quad (9)$$

$$K_r = PHI * (K_{max}(ol) \left(1 - \frac{x - x(ol)}{R(ol)} \right) - K_{max}) \quad (10)$$

$$PHI = \frac{1 - K_{thres}/K_{max}}{SOR - 1} \quad (11)$$

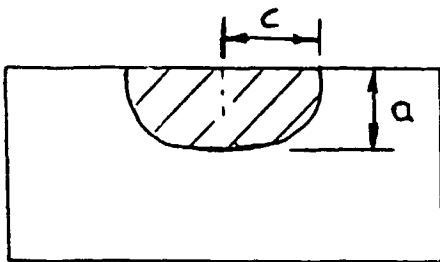
$$R_y(ol) = \frac{1}{PSX * \pi} \left(\frac{K_{max}(ol)^2}{YLD} \right) \quad (12)$$

The subscript (ol) refers to an overload condition. It is changed each time that a maximum load exceeds a previous maximum, or when the current yield zone (R_y) grows beyond the yield zone created by an overload ($R_y(ol)$). PHI is simply a parameter used in the Generalized Willenborg model. K_{thres} is taken as the lowest value of K that will cause a crack to grow for $R = 0$. This is often referred to as the K threshold for $R = 0$ (which is the same as K threshold since $R = 0$). SOR

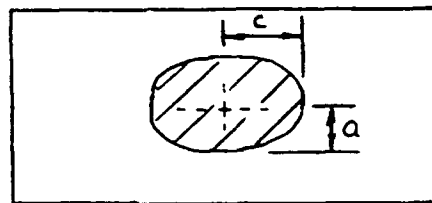
is known as the overload shut-off-ratio and is the ratio of the overload maximum stress to the subsequent minimum stress required to stop further crack growth. In practice, values for SOR generally range from 2 to 3. The variable, PSX, is a value from 2 (plane stress) to 6 (plane strain) which indicates the state of stress in the crack growth direction. YLD is simply the yield strength of the given material.

Stress Intensity Factor Solutions

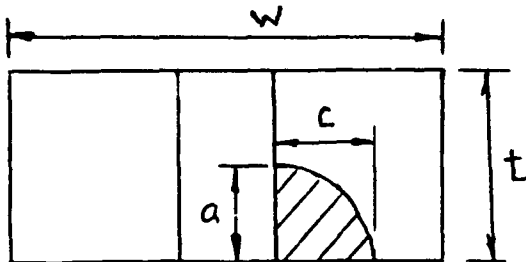
MODGRO has stress intensity factor solutions for 10 common structural geometries built into subroutines. The geometries are as follows.



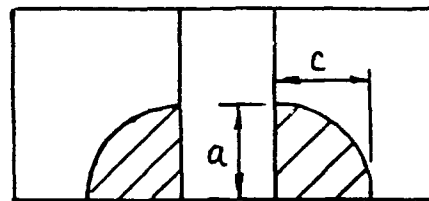
Semi-elliptical Surface Flaw



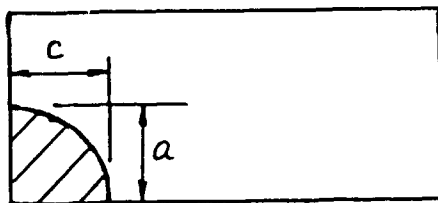
Full Elliptic Embedded Flaw



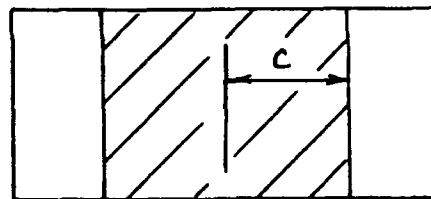
Single Corner Crack at a Hole



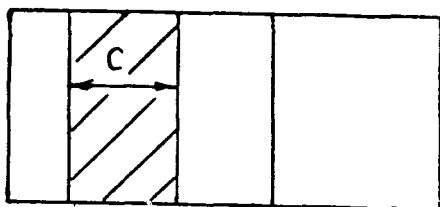
Double Corner Crack at a Hole



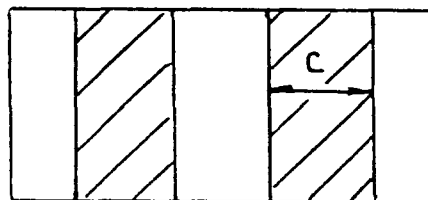
Single Edge Corner Crack



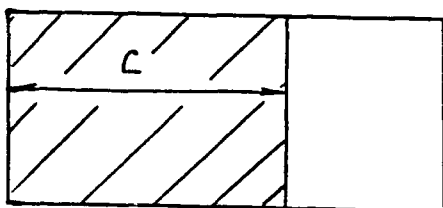
Center Through Crack



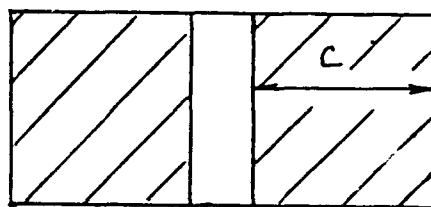
Single Through Crack at a Hole



Double Through Crack at a Hole



Single Edge Through Crack



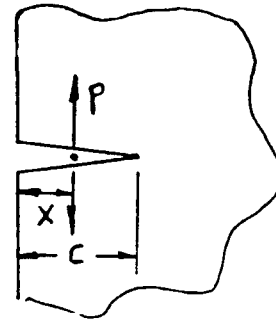
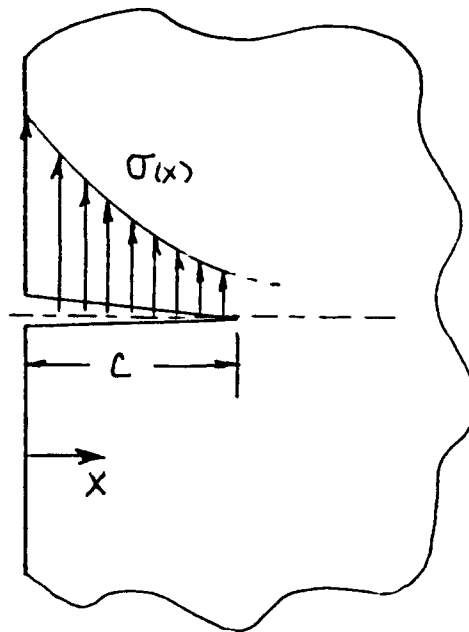
Double Edge Through Crack

These stress intensity factor solutions were developed by J. Newman and I. Raju at NASA Langley (Ref. 1).

When using a part-through flaw solution, MODGRO will automatically transition to the appropriate through flaw solution as soon as the crack is predicted to penetrate the thickness. While this method is not strictly accurate, it should not be a cause for much error. In general, the transition from a part-through crack to a through-the-thickness crack occurs over a relatively short period of time (Ref. 2).

In addition to the subroutines, MODGRO allows the stress intensity factors to be modified in the program by the use of multiplication factors. These factors (or beta factors as they may be called) provide a means of approximating the stress intensity solutions for structures that differ from the standard solutions due to geometric or loading considerations.

The beta factors are calculated by the pre-processor for MODGRO (MODINP). They are based on the unflawed stress distribution in the crack plane. The point load solution for an embedded crack in an infinite plate is integrated using the unflawed stress distribution in each crack growth direction. This is illustrated below for a one-dimensional case.



The solution for the non-uniform case to the left is based on a curve fit solution for the above geometry found in Reference 2, p. 8.3.

$$K_I = \int_{-c}^c \sigma(x) \cdot F(c,x) dx$$

$$F(c,x) = \frac{2}{\sqrt{\pi c}} \frac{1.3 - .05(x/c) - .2(x/c)^2 - .3(x/c)^3 + .25(x/c)^4}{\sqrt{1 - (x/c)^2}}$$

The resulting beta factors are stored for one or two crack growth directions as functions of crack length. Since the factors are ratios of the integrated point load solution to the uniformly loaded embedded flaw, they should be used to modify the appropriate, non-holed, standard solution. A standard hole solution may be used only if the stress distribution is normalized to that of an open hole in an infinite plate. In addition, actual geometries must be simulated to agree with the standard solutions. It is sometimes necessary to model an off-center crack by using the width of the cracked side and doubling it. Of course, for edge cracks this does not apply.

Stress intensity factors have been calculated with this approach for edge and surface cracks in bending, and for corner cracks at holes (using the stress distribution for an open hole in an infinite plate). The accuracy was generally within 3-4% for all crack lengths where the standard solution was valid. The worst case was a 16% error for a relatively long through crack.

Spectrum Modelling

Unlike CRKGRO, MODGRO only accepts spectrum input in one form. That

form is: maximum, minimum, number of cycles. A cycle-by-cycle spectrum may be input by specifying one cycle per max-min pair. The word stress is not used here because the spectrum could be input in a normalized form or in terms of load. A parameter called the 'stress multiplication factor' is used to convert the numbers in the spectrum to stress. The units can be anything that the user desires as long as all other input parameters are consistent.

MODGRO will accept virtually any size spectrum since the spectrum input is taken by as many as 999 separate data files. The practical limitation will be run time because of the number of calculations involved when larger spectra are used. Details of the spectrum input are given in the users guide.

Vroman Integration Technique

MODGRO uses the Vroman integration technique when a blocked spectrum (more than one cycle per max-min pair) is input. The program calculates the crack growth rate for each new stress level then determines the amount of growth that would occur over the given number of cycles. However, since the user is asked to input a maximum percent crack growth increment, a limit is placed on the amount of crack extension. When the given amount of crack extension is reached, the program recalculates the crack growth rate for the new crack length. This method provides a compromise between the accuracy of a cycle-by-cycle calculation and a time savings of a straight Vroman integration. The percent crack growth value is left to the users discretion. It is; however, recommended that the value not exceed 10% in order to minimize any error caused by not recalculating the crack growth rate as the crack grows.

MODGRO USERS GUIDE

There are two (2) ways to create input model and spectrum information files for use in MODGRO. The first is to use the pre-processor, MODINP, and the second is to create the files using a text editor. The first part of this guide will explain the use of MODINP. Samples of model and spectrum files will also be given in Appendix A if the user wishes to create his/her own files without using MODINP. It is, however, suggested that MODINP be used in order to minimize the possibility for error.

NOTE: As was previously mentioned, no units are assumed for the input. It is the responsibility of each user to insure the consistency of any units used. Of course, the output will also be in the chosen units.

Using MODINP

MODINP is used to interactively create and edit model and spectrum files used by MODGRO. Its use will insure that the necessary format is maintained.

File Options

After the program title and version appear on the screen, the user will be prompted to: 'HIT ANY KEY TO CONTINUE'. The following prompt will then be displayed.

TYPES OF INPUT DATA TO BE PROCESSED:

- 1) MODEL DATA ONLY
- 2) SPECTRUM DATA ONLY
- 3) BOTH MODEL DATA AND SPECTRUM DATA

CHOICE : _

Spectrum and model input data are stored in separate files and may be created and/or edited separately. This is useful when it becomes necessary to run the same model data for a different spectrum or vice versa.

After a choice is made, the user is reminded that the data will be stored on a file of the users' choosing. Also, instructions are given on how to handle typing or other errors.

Processing Model Data

In this case, model data is defined as any input data that is not necessary to directly describe the loading or stress spectrum. There are some parameters dealing with the spectrum in the model file, but they are merely modification parameters.

The first question asked is the following.

DO YOU WISH TO EDIT AN EXISTING INPUT DATA FILE? (Y-N) : _

The only accepted response is Y or N (upper or lower case). The enter key should not be pressed when responding to (Y-N) questions. If the response is no (N), the user will be prompted for the required model data. If the user wishes to edit an existing input model file, he/she will be prompted for the filename (with the drive letter if necessary). In the latter case, only the editing functions of MODINP will be used.

Entering Title and Geometry Data

The first prompt here is the title prompt.

TITLE: _

This title is used to describe the model and distinguish it from other files that may be run on MODGRO. It should be kept to 72 columns so that it will fit on the screen and standard printer paper.

The next prompt is for the stress intensity factor solution.

STRESS INTENSITY SOLUTIONS:

CODE 1010 CENTER SEMI ELLIPTIC SURFACE FLAW
CODE 1020 CENTER FULL ELLIPTIC EMBEDDED FLAW
CODE 1030 SINGLE CORNER CRACK AT A HOLE
CODE 1040 SINGLE SURFACE CRACK AT A HOLE
CODE 1050 DOUBLE CORNER CRACK AT A HOLE
CODE 1060 DOUBLE SURFACE CRACK AT A HOLE
CODE 1070 SINGLE EDGE CORNER CRACK
CODE 2010 CENTER THRU-CRACK
CODE 2020 SINGLE THRU-CRACK AT A HOLE
CODE 2030 DOUBLE THRU-CRACK AT A HOLE
CODE 2040 SINGLE EDGE THRU-CRACK
CODE 2050 DOUBLE EDGE THRU-CRACK

Enter: CRACK CODE CHOICE, ICODE = _

For a description of these models, refer to the background section of this report.

The user will then be asked to input the initial crack length(s).

ENTER CRACK GEOMETRY:

INITIAL SURFACE CRACK LENGTH, CI = _

and, if appropriate

INITIAL DEPTH CRACK LENGTH, AI = _

Again, it is important to refer to the illustrations given in the

background section for geometric nomenclature.

The next series of prompts deal with the plate geometry.

ENTER PLATE GEOMETRY

PLATE THICKNESS, THK = _ (only asked if modelling a part thru flaw)

PLATE WIDTH, W = _

and, if appropriate

HOLE RADIUS, RAD = _

WHAT PERCENT OF THE LOAD IS TRANSFERRED THROUGH THE HOLE?

(A VALUE FROM 0 TO 100 - 0 FOR AN UNLOADED HOLE, (-1) IF OPEN AND UNLOADED)

Enter: PERCENT LOAD TRANSFER, PLT = _

The ability to analyze for various values of load transfer has been taken directly from ASDGRO.

NOTE: In the case of an edge type flaw, the geometry input is straight forward. The other solutions have a symmetry condition that is important to consider if modelling a real crack growth problem. A possible solution for modelling an unsymmetric case is to assume that the width is equal to twice the distance from the centerline to the edge of the cracked side. If both sides are cracked, then the shortest side can be doubled. The latter will yield a conservative answer. In either case, the error will be minimal if the initial crack is relatively short.

Once the geometry information has been entered, a summary of the user supplied data are listed and the following question is asked.

IS EVERYTHING OK? (Y-N) _

At this point the user has the opportunity to check the input data. If any errors exist, simply respond with a 'N' (upper or lower case). The program will ask whether the user wishes to change an entry beginning with the first (title), and ending with the last geometry data entry. An example of this is as follows.

CHANGE CRACK MODEL CODE? (Y-N) _

Each of these prompts appear under a list of the current values of the input data. If the response is 'N', then the next prompt is displayed. If a change is desired, the appropriate prompt is displayed at the bottom of the screen. When the new value is entered, it will appear in the summary at the top of the screen. Finally, the 'IS EVERYTHING OK?' question will be asked again. The entire sequence will be repeated until the user responds with a yes (Y) to this question.

When the user signals that the data is good to this point, the following prompt is displayed.

DO YOU WISH TO MODIFY THE STRESS INTENSITY SOLUTION
BY IMPOSING A NON-UNIFORM STRESS FIELD? (Y-N) : _

At this point, the user has the ability to modify the standard stress intensity solution. For example, the solution for an edge corner cracked plate in bending can be approximated by entering the normalized bending stress distribution in each crack growth direction. A value of one (1) is assumed in each direction at the point where each crack length is zero (0). All stress values are normalized to the above standard, and the stresses used by MODGRO will be assumed to apply at the location of zero (0) crack length. The program asks for a 'radius' value (2) and the normalized stress values in the x and y (c and a) crack directions. Generally, the values for the c direction are necessary after a radius larger than the thickness is input. In cases where the stresses for a given dimension are unnecessary, do not enter zero (0). Simply continue to repeat the last useful normalized value until finished.

Remember, it is important to be sure that the entire crack growth range is covered by the normalized stresses.

The routine that determines the beta correction factors for MODGRO using the normalized stress distribution allows the data to be entered via the keyboard or from an external file. Using an external file can be advantageous if some kind of a sensitivity study is being conducted. The format is the same as used in the keyboard entry.

When finished with this portion of the pre-processor, the following prompt appears.

DA/DN - DELTA K RELATION TYPES:

- 1) WALKER EQUATION
- 2) TABULAR DATA

CHOICE : _

The standard Walker equation can be used with as many as five (5) segments. If chosen, the program will ask for all of the required parameters, such as: C, m, p, and Kcut (refer to the background section). The value Kcut is the value of K (R=0) above which the next segment is used. Within this section of the program, typing errors are handled in a slightly different manner. After a number of questions are asked, the user is prompted with the 'IS EVERYTHING OK?' prompt. If the answer is no, 'N', then each question is asked again. Therefore, when a mistake is made entering data for the Walker equation, it is best to enter dummy data until the prompt is given. Then simply redo the entire input. This was done because of the large number of input values required.

The tabular data option requires that an external file be resident in the current directory. The file is: MATFILE.DAT. It contains tabular da/dN data for a variety of metallic materials. The program lists the

title for each material in the database. In addition to the material type, the title also gives the units used in the data. This is extremely important since unit consistency must be maintained in the input. At the present time, data for a few materials are present in the file. These should be used as samples for the addition of more data. There is no limit to the number of materials that may be used. It is only limited by the users disk space.

The material titles are displayed on the screen and the user is asked for a choice. When the screen is full, the user may type zero (0) to continue the listing.

The data in MATFILE.DAT consists of the following information.

Title,
da/dn, delta K (R=0), Walker m (25 lines required)
R(low), R(high), KIC (plane strain fracture toughness), Yield

R(low) and R(high) refer to limiting values of R below and above which no Walker shift is applied. Since MODGRO sets delta K equal to Kmax when $R < 0$, there is a negative value of R below which there is no additional shift in the plotted data. This effect may also be seen in plots of the crack opening load vs. R value curve. However, it should be noted that the above data are used by MODGRO assuming that standard LEFM conditions apply. When the stress levels are high enough to cause local yielding (other than at the crack tip), the 25 point shifting method may result in some error.

For an explanation of how to determine the Walker m values, refer to the background section.

In order for the program to know when data for the last material has been input, it is necessary to include the word 'end' as the last line in the file. The program reads it as if it were a title then ends if it is the word 'end'.

As soon as the crack growth rate information has been entered, the next prompt appears.

Enter: '2' FOR A PLANE STRESS OR '6' FOR A PLANE STRAIN SOLUTION

IN THE C DIRECTION, PSC = _

and, if appropriate

IN THE A DIRECTION, PSA = _

These values provide a means of approximating the actual value of fracture toughness in each crack growth direction. The program assumes that the maximum delta K value (R=0) is the plane stress fracture toughness. It simply uses a linear interpolation between that and the input value of the plane strain toughness to determine the actual value in each direction. If the Walker equation is used, and the highest Kcut is less than the input toughness, no interpolation is effective. In

that case, the input plane strain value is used.

The next prompt is for the retardation model.

SHUT OFF OVERLOAD RATIO (0 = NO REDARDATION EFFECTS) : _

The value used here may not fall in the range (0, 1). If a number in that range is input, it will be set equal to zero (0), and no retardation will be modelled. This parameter is used by the modified, generalized Willenborg model to indicate the overload required to essentially 'shut off' further crack extension.

STRESS MULTIPLYING FACTOR FOR THE SPECTRUM : _

The value input here is multiplied by the minimum and maximum values for load or stress used in the spectrum. Hence, a normalized spectrum may be used with the above value to convert the values to the appropriate stress. For the standard stress intensity models, the gross section stress is used. When using the stress intensity modification parameters, the stress must be the unflawed stress at the zero (0) crack length location ($z = 0$).

RESIDUAL STRESS USED FOR CRITICAL CRACK SIZE DETERMINATION

Note: If zero is used here, failure will be based only on actual K values calculated from the input stress spectrum.

RESIDUAL STRESS REQUIREMENT : _

If a value other than zero (0) is used here, a check is made on K_{max} for this stress value for each crack direction. If K_{max} for this stress exceeds the applicable fracture toughness, then failure occurs. The only exception for this is when the failure occurs in the 'a' direction for a part through flaw, and the crack length 'c' would not fail if considered to be a through crack. In this case, the crack is immediately transitioned to a through crack and continues to grow.

The value used for the residual stress is not multiplied by the stress multiplying factor. It must meet all of the requirements for stress values mentioned above.

After this data has been entered, the input data will be displayed in a summary table as was previously discussed for the title and geometry data. The same procedure will be repeated for the purpose of editing data (if necessary). When this data is considered to be 'OK', then the model input data are complete and the next prompt will appear.

Enter - DRIVE:FILENAME.EXT - FOR CURRENT INPUT DATA FILE

-

If no drive letter is used, the file will be stored in the current directory under the specified name.

Processing Spectrum Information

Spectrum data is simply the data required to define the load/stress history for a given crack growth analysis. As was mentioned in the background section, the only excepted input format is (max, min). This should not pose a problem since it is a simple matter to convert other forms to this standard.

MODINP does not create or edit the actual max, min spectrum values. These are stored in one or more separate data files. An example of the file format for the data is given in Appendix A. The spectrum information that is created in this program is only descriptive in nature.

As is the case with the model data, the first prompt deals with the option to edit an existing file.

DO YOU WISH TO EDIT AN EXISTING SPECTRUM INFORMATION FILE? (Y-N) : _

If the response to this question is yes, the user is asked for the spectrum file name and is given the opportunity to change certain items. Otherwise, the next prompt appears.

SPECTRUM TITLE : _

It is advisable to keep the title to a maximum of 60 characters so that it, along with the heading, is printable on standard paper. It is very useful in quickly identifying which spectrum was used in a given analysis.

TYPE OF SPECTRUM :

- 1) CYCLE BY CYCLE
- 2) BLOCKED CYCLES

CHOICE : _

A cycle by cycle spectrum is one in which each max-min load/stress is applied for one (1) cycle. This may be thought of as a real time spectrum. The blocked spectrum is one where each max-min pair is applied for some finite number of cycles. Many times, spectra are presented in this format to save computer time and space. In many cases, the use of the blocked format produces very little difference in terms of the analysis. In general, the more times a spectrum is repeated, the less the difference in using blocked or cycle-by-cycle spectra.

SUB-SPECTRUM LABEL (IE: FLIGHT, MISSION, GROUP, ETC.)

THE ACTUAL SPECTRUM STRESSES ARE DIVIDED INTO GROUPS OF STRESS LEVELS AND CYCLES (MAX OF 1205 LEVELS PER SUB-SPECTRUM). THE LABEL USED HERE DEFINES WHAT THE SUB-SPECTRUM GROUPS SHOULD BE CALLED.

LABEL : _

This feature provides flexibility for the user. A spectrum can be thought of in terms of many different quantities. It may be advantageous to present results in terms of days, blocks, or any number of different time units. What is entered here will be the label given to the units of each sub-spectrum in the analysis. Furthermore, it will appear exactly as entered. It should be noted here that several sub-spectra may be stored in the same data file. It is not necessary to create a new file for each sub-spectrum. It is, however, necessary to define each sub-spectrum by a number and the number of levels it contains. The size of each spectrum data file is up to the user, but it is advisable to keep them small enough to be edited on the PC. The format will be discussed at the end of the users guide.

THE ACTUAL SPECTRUM STRESS DATA CAN BE STORED IN AS MANY AS 999 SEPARATE DATA FILES. EACH FILE MUST HAVE THE SAME ROOT NAME WITH A 3 DIGIT I.D. NUMBER ATTACHED (IE: TWIST001.DAT). THE PROGRAM NEEDS TO KNOW HOW MANY FILES ARE USED IN DEFINING YOUR SPECTRUM.

NUMBER OF SPECTRUM FILES : _

This input is required so that the program can keep track of the number of times that the entire spectrum has been repeated. It is also used to allow the program to keep track of the file to be opened once the current file has been read.

At this point, MODINP will repeat the input information and ask 'IS EVERYTHING OK?'. If not, the user is given the chance to edit the data as was done in the model input. The format for the spectrum information file is as follows:

Spectrum Title
Spectrum Type (1-cyclexcycle, 2-blocked)
Sub-Spectrum Label
Number of Spectrum Files

Once the user is satisfied with the data, MODINP will ask the user for a location to store the spectrum information.

THE FILENAME OF THE SPECTRUM INFORMATION FILE MUST HAVE A '.DAT' EXTENSION. THE NAME MAY NOT EXCEED 5 CHARACTERS SINCE A 3 DIGIT IDENTIFIER MUST BE ATTACHED TO THE FILES CONTAINING THE ACTUAL STRESS DATA. THE '.DAT' EXTENSION WILL BE ADDED TO THE INPUT NAME, SO DON'T INCLUDE IT IN THE INPUT FILENAME. DO NOT USE ANY SUB-DIRECTORIES - THEY WOULD BE TAKEN AS PART OF THE NAME.

Enter - DRIVE:FILENAME - OF CURRENT SPECTRUM INFORMATION FILE

-

If the drive is not specified, it will be stored in the current directory under the name entered.

When MODINP has finished storing all the the required data, it will display the following message.

***** DONE *****

Using MODGRO

MODGRO requires some input from the user to utilize the desired program options. This input has been kept to a minimum. It is summarized below.

After the title has been displayed, the user is prompted to 'HIT ANY KEY TO CONTINUE'. The screen is cleared and the next prompt appears.

Enter - DRIVE:FILENAME.EXT - OF MODEL DATA FILE : _

If the drive is omitted, the current drive is assumed.

Enter - DRIVE:FILENAME - OF SPECTRUM INFORMATION FILE **NO EXTENSION**
MUST MATCH THE ROOT NAME OF THE SPECTRUM FILES
IE: C:ROOTNAMEXXX (THE '.DAT' EXTENSION IS
AUTOMATICALLY ASSUMED BY THE PROGRAM)

Enter NAME : _

After the input data has been read, the next prompt appears.

NUMBER OF TIMES THE SPECTRUM IS TO BE REPEATED : _

The spectrum referred to here is the ENTIRE spectrum including all of the spectrum files. When the specified number of repeats is finished, the program will halt. When halted for this reason, a message will be displayed to inform the user that the specified number of repeats has been accomplished.

The next prompt deals with the output print options for the analysis.

PRINT OPTIONS FOR THE OUTPUT OF CRACK GROWTH DATA:

PRINT OUTPUT DATA AT 1) SPECIFIED CRACK GROWTH INCREMENTS
2) SPECIFIED SPECTRUM TIME INCREMENTS
3) END OF EACH SPECTRUM STRESS LEVEL

CHOICE : _

In any case, crack growth information is printed after the first stress level. If output is desired for specific growth increments, the user is asked for the increment.

Enter: CRACK GROWTH INCREMENT BETWEEN DATA PRINTINGS : _

The program will print out data after each growth increment is reached in either direction. If an increment is passed, for any reason, the program will attempt to get back on track as soon as possible.

If output is desired for a specified time increment, the following prompt appears.

DO YOU WANT DATA PRINTED IN INTERVALS OF :

- 1) CYCLES, OR
- 2) 'SUB-SPECTRUM LABEL' NUMBERS

CHOICE : _

This provides additional flexibility to the user since it may be more appropriate to print results after a given number of sub-spectra have been repeated. After the choice is made, the program asks for the printing interval.

Enter: NUMBER OF 'UNITS' BETWEEN DATA PRINTINGS : _

The program will print data after the specified number of 'units' has been reached. In both of the above cases, the exact interval may not be kept since the program must finish a given stress level before printing results. It is possible for a given interval to be reached within a block of cycles in a given stress level. However, the program attempts to return to the desired intervals.

If the last option is chosen, to print after each stress level, it will do just that. This can be excessive for large spectra. It is useful for some cases, especially to check the crack growth calculations. If the option is picked, a message to that effect will appear immediately, giving the user the opportunity to abort the run by typing (CNTL-C).

If the user has chosen a blocked spectrum, the next prompt will be displayed.

MAXIMUM PERCENT CRACK GROWTH INCREMENT (FOR BLOCKED SPECTRA) : _

This value should be input as a percent (no decimals). Its purpose is to limit the Vroman integration as discussed in the background section. Normal values range from 1 to 10 percent.

The next prompt gives the user the option to direct the output to different devices.

OPTIONS FOR INPUT DATA ECHO AND WRITING OUTPUT DATA

SEND DATA TO: 1) SCREEN
 2) SCREEN AND PAPER PRINTER
 3) SCREEN AND DISK FILE

CHOICE : _

These choices are self-explanatory. As may be seen, data is always output to the screen. If output is directed to a disk file, the program will prompt the user for a DRIVE:FILENAME.EXT for data storage.

The next prompt is for the storage of the crack growth data for plotting by some external plotting routine.

DO YOU WANT THE CRACK GROWTH DATA SAVED FOR LATER PLOTTING? (Y-N) : _

The program will store crack length vs. time for each crack dimension in a user specified file. The file is stored in ASCII format and can be easily modified for use in any plotting package.

After the above input, the program will echo the input information. The program then proceeds with the analysis.

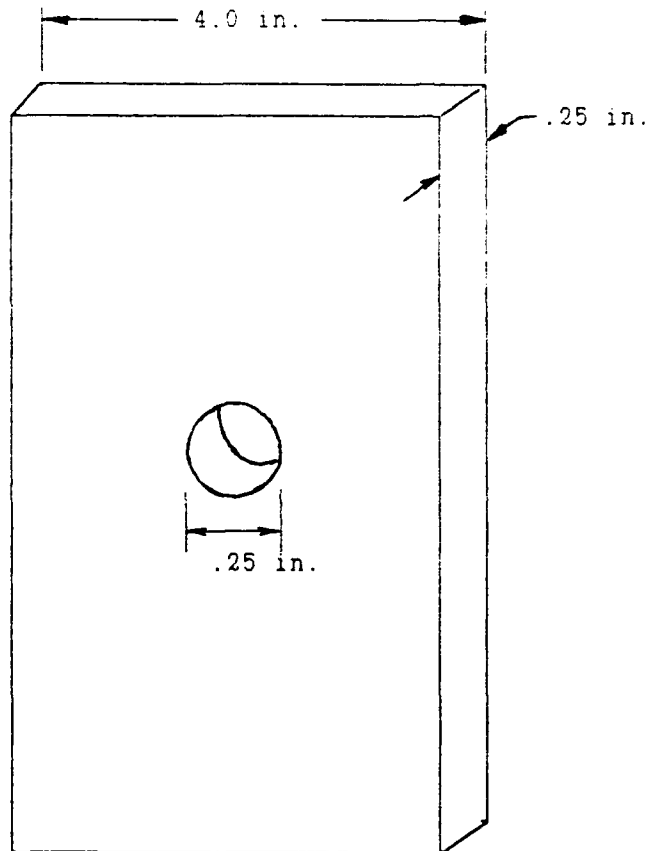
REFERENCES

- 1) Newman, J.C., Jr., and Raju, I.S., 'Stress Intensity Factor Equations for Cracks in Three Dimensional Finite Bodies,' NASA TM 83200, Langley Research Center, Hampton, VA, 1981.
- 2) Grandt, A.F., Harter, J.A., and Heath, B.J., 'The Transition of Part-Through Cracks at Holes Into Through-the-Thickness Flaws,' ASTM STP 833, 15th National Symposium on Fracture Mechanics, July, 1982, pp. 7-23.

APPENDIX A

SAMPLE RUN OF MODGRO USING THE MODINP PRE-PROCESSOR

A sample case was run, using MODINP, to provide an example for reference. The geometry is as follows :



The input data was generated using MODINP. The format of the input file is given below.

TEST CASE FOR A SINGLE CORNER CRACK AT A HOLE

1030
.05
.05
.25
4
.125

```

0
0
2
6061-T6511 EXTRUSION (IN-KSI)
1E-09      2.401      .502
2E-09      2.411      .513
1E-08      2.681      .53
2E-08      2.981      .535
4E-08      3.302      .54
6E-08      3.552      .551
.0000001   3.992      .553
.0000002   4.602      .554
.0000004   5.432      .555
.0000006   6.003      .569
.0000008   6.453      .574
.000001    6.803      .607
.000002    8.253      .622
.000004    10.054     .634
.00001     13.355     .605
.00002     16.997     .591
.00004     21.109     .583
.0001      26.412     .533
.0002      31.015     .53
.0004      34.516     .526
.0006      36.318     .518
.0008      37.519     .504
.001       38.52      .493
.004       39.52      .483
.01        40.021     .483
35
-.3         .72
56
2.25
3
3
1
0

```

The spectrum information file was also generated with MODINP and is given below.

```

TEST SPECTRUM
2
FLIGHT
1

```

The first line is obviously the title line for the spectrum; however the other lines may not be as apparent. The next line indicates that the spectrum will be blocked (2) instead of cycle by cycle (1). This is important only because of the Vroman integration technique. If the

spectrum is blocked, MODGRO will ask the user to input a percent value that should not be exceeded for every block of cycles encountered. The next line is the label to be given to each individual group of stress/load values in the spectrum. The last entry tells how many files contain the actual spectrum data.

In this case, only one file is used for the spectrum, and one group of stress values is used. Notice the format in the file given below.

1	7	
20.00	-5.00	5000
25.00	10.00	1000
15.00	3.00	3000
28.00	-2.00	100
10.00	0.00	4000
20.00	10.00	2000
35.00	-5.00	1

The first line contains the group number (in this case, flight number) and the number of max, min stress values in the group. Of course, the next 7 lines contain the maximum stress, minimum stress, and number of cycles. If the spectrum were cycle by cycle, the number of cycles, in each line, would be unity.

It is important to notice that the format for all spectra is the same. If more groups (flights, blocks, etc.) were required, the format shown above would simply be repeated with the appropriate heading line as above. For example, the next line would look like this:

2	15
---	----

This indicates that group 2 has 15 lines in it. This can be continued for as many groups as necessary. However, do not insert blank lines in the spectrum files. MODGRO reads the number of lines indicated in the header for each group and looks for an end-of-file to indicate that the data is terminated. As was mentioned in the users guide, up to 999 spectrum files may be used. A user will run out of patience waiting for a run to finish long before spectrum storage space is gone. This assumes that a hard disk is being used to store very large spectra. MODGRO will only look for the spectrum files on one drive and will not prompt the user for a new floppy disk.

The output generated by MODGRO is given in the following pages.

AFWAL/FIBEC CRACK GROWTH ANALYSIS PROGRAM (MODGRO) Version 1.3

TIME: 16:19:26 DATE: 02-11-1988

INPUT DATA FILE intest.dat
SPECTRUM DATA FILE tspec

TITLE: TEST CASE FOR A SINGLE CORNER CRACK AT A HOLE

CRACK CODE = 1030 SINGLE CORNER CRACK AT A HOLE
INITIAL SURFACE CRACK LENGTH, CI = .05
INITIAL CRACK DEPTH, AI = .05
PLATE THICKNESS, THK = .25
PLATE WIDTH, W = 4
HOLE RADIUS, RAD = .125

% LOAD TRANSFER = 0 (A NEGATIVE NUMBER INDICATES AN OPEN HOLE)

TABULAR RATE DATA WERE USED
MATERIAL: 6061-T6511 EXTRUSION (IN-KSI)

FRACTURE TOUGHNESS = 35
SHUTOFF OVERLOAD RATIO = 2.25
RESIDUAL STRESS REQUIREMENT = 0
YIELD STRENGTH = 56

MAXIMUM PERCENT CRACK GROWTH INCREMENT, PCG = 3 %

A PLANE STRESS SOLUTION IS USED IN THE A DIRECTION: PSA = 3.0
A PLANE STRESS SOLUTION IS USED IN THE C DIRECTION: PSC = 3.0

***** INPUT STRESS SPECTRUM:

SPECTRUM TITLE: TEST SPECTRUM

THE SPECTRUM IS REPEATED A MAX. OF 1000 TIMES

THE STRESS SPECTRUM MULTIPLICATION FACTOR = 1.0000E+00

***** CRACK GROWTH ANALYSIS RESULTS

DATA IS PRINTED EVERY .05 CRACK GROWTH UNITS

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	5.049E-02	1.158	-0.250	9.183E+00	4.6960E-06
A	5.149E-02	1.664	-0.250	1.319E+01	1.4164E-05
Max. Stress = 2.000E+01			R = -0.25		
105 CYCLES FLIGHT:			1	PASS:	1 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	7.181E-02	1.295	-0.250	1.218E+01	1.1292E-05
A	1.014E-01	1.424	-0.256	1.577E+01	2.4158E-05
Max. Stress = 2.000E+01				R = -0.25	
2786 CYCLES FLIGHT:				1	PASS: 1 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	9.574E-02	1.292	-0.250	1.402E+01	1.6851E-05
A	1.530E-01	1.322	-0.255	1.799E+01	3.6692E-05
Max. Stress = 2.000E+01				R = -0.25	
4480 CYCLES FLIGHT:				1	PASS: 1 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	1.022E-01	1.288	-0.251	1.443E+01	1.8295E-05
A	1.672E-01	1.301	-0.250	1.858E+01	4.0430E-05
Max. Stress = 2.000E+01				R = -0.25	
4841 CYCLES FLIGHT:				1	PASS: 1 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	1.164E-01	1.247	-0.712	5.242E+00	6.3432E-07
A	2.023E-01	1.249	-0.720	6.849E+00	1.8364E-06
Max. Stress = 1.500E+01				R = 0.20	
9000 CYCLES FLIGHT:				1	PASS: 1 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	1.301E-01	1.271	-2.115	6.443E+00	1.4686E-06
A	2.377E-01	1.196	-2.146	8.096E+00	3.3435E-06
Max. Stress = 2.000E+01				R = -0.25	
17171 CYCLES FLIGHT:				2	PASS: 2 FLIGHT NUMBER: 1

***** TRANSITION TO A THRU-CRACK AT 95% PENETRATION

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	1.340E-01	1.402	-1.012	1.114E+01	9.3201E-06
Max. Stress = 2.000E+01				R = -0.25	
17589 CYCLES FLIGHT:				2	PASS: 2 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	1.508E-01	1.381	-0.254	1.867E+01	4.1425E-05
Max. Stress = 2.000E+01				R = -0.25	
18220 CYCLES FLIGHT:				2	PASS: 2 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	2.024E-01	1.313	-0.256	2.054E+01	6.0303E-05
Max. Stress = 2.000E+01				R = -0.25	
19220 CYCLES FLIGHT:				2	PASS: 2 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	2.560E-01	1.243	-0.258	2.184E+01	7.6781E-05
Max. Stress = 2.000E+01				R = -0.25	
19987 CYCLES FLIGHT:				2	PASS: 2 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	3.037E-01	1.177	0.400	1.709E+01	4.0292E-05
Max. Stress =		2.500E+01		R = 0.40	
21101 CYCLES		FLIGHT:		2	PASS: 2 FLIGHT NUMBER: 1

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	3.554E-01	1.114	0.316	1.160E+01	1.0277E-05
Max. Stress =		2.000E+01		R = 0.50	
29208 CYCLES		FLIGHT:		2	PASS: 2 FLIGHT NUMBER: 1

FRACTURE TOUGHNESS OR CRITICAL CRACK SIZE HAS BEEN REACHED
 FAILURE HAS OCCURED IN SPECTRUM PASS NUMBER: 2
 DURING FLIGHT NUMBER 1
 AFTER 1 CYCLE(S) OF STRESS LEVEL NUMBER 7

	Crack Size	Beta	R(eff)	Delta-K	D()/DN
C	3.792E-01	1.082	-0.143	4.078E+01	1.0000E-02
Max. Stress =		3.500E+01		R = -0.14	
30202 CYCLES		FLIGHT:		2	PASS: 2 FLIGHT NUMBER: 1

RUN TIME = 0 hr. 0 min. 59 sec.